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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study investigated the use of optical correlation (holography) as a tool for the detection of surface changes, including those induced by fatigue, and its applicability for the nondestructive evaluation of strain and fatigue damage, and the prediction of impending failure in structural alloys.

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FATIGUE DAMAGE DETECTION IN STEELS

BY OPTICAL CORRELATION

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15 March 1985

U.S. Army Research Office
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to

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A. Statement of Problem

Fatigue caused by cyclic stress or strain is a major cause of failure in engineering components and structures. The failure is often unexpected and may be catastrophic, yet no reliable method exists for the detection of fatigue damage by nondestructive means prior to the development of macrocracks, or for the prediction of impending failure by nondestructive evaluation early in the fatigue life.

In materials and components that are not precracked, much of the fatigue life is spent in the initiation and early growth of microcracks, usually at or near the external surface. This study investigates the use of optical correlation (holography) as a tool for the detection of surface changes, including those induced by fatigue, and its applicability for the nondestructive evaluation of strain and fatigue damage, and the prediction of impending failure in structural alloys.

B. Summary of Results

The optical correlation technique consists in measuring the peak correlation intensity (I_c) of a reconstructed reference beam of light, formed when a coherent beam scattered from the surface of an object is filtered by a hologram containing information about the surface topography at an earlier time. In principle, I_c can then be used as a measure of surface change.

In this investigation, surface changes in engineering alloys caused by various kinds of mechanical deformation were carefully characterized. The deformation studies included abrasive wear, elastic strain, and plastic strain as well as fatigue cycling in order to evaluate independently the various possible contributions to correlation intensity changes ob-

served during fatigue. Correlation intensity measurements were also made during the deformation experiments. Relationships were then established between I_c data and the appropriate deformation parameters, and where possible, these relationships were compared with the predictions of analytical models developed as part of this investigation. Major results are as follows:

1. Abrasive Wear

Surface changes caused by abrasion were documented by optical microscopy for A286 stainless steel, and related quantitatively to the corresponding correlation intensity changes. The holographic technique provides a sensitive method of detecting and quantifying abrasive wear damage on the metal surface. The method is applicable for both initially polished and initially rough surfaces. An analytical model was developed to account for the observed changes in I_c with abrasion: results derived from the model agree qualitatively with the experimental data. These results demonstrate conclusively that optical correlation intensity is sensitive to topographic changes on the surface of materials, and can be used for the nondestructive evaluation of wear.

2. Elastic Strain

Experiments on a high strength aluminum alloy tested in simple tension show that I_c is sensitive to applied elastic strain: I_c falls by approximately 5% for each elastic strain increment of 10^{-3}. The response curve is reversible and is in good agreement with results derived analytically on the basis of a model of reversible topographic changes on the metal surface. The correlation technique can be used to monitor elastic strains applied to specimens with either polished or rough surfaces.

3. Plastic Strain

Experiments were conducted to relate correlation intensity data to applied uniaxial plastic strain in 2024-Al alloy, and to investigate the relationship between I_c, plastic strain, and changes of surface topography in A286 stainless steel.

The results demonstrate that I_c is an irreversible function of plastic strain (ε_p), obeying the relationship

$$I_c = I_c^o \exp(-B\varepsilon_p) \qquad (1)$$

where I_c^o is the correlation intensity prior to the application of strain, and B is a parameter whose numerical value depends on the slip character of the material. The relationship between I_c and ε_p depends only weakly on the initial surface roughness. These results demonstrate that the correlation intensity technique can be used for the evaluation and measurement of plastic strain.

4. Fatigue

Surface changes accompanying fatigue deformation, crack initiation and microcrack growth were characterized in detail for two aluminum alloys, and for A286 stainless steel after different heat treatments. Microcrack densities and propagation rates were determined as a function of stress amplitude, in both the low cycle and high cycle regimes. Fatigue damage for each material is strongly stress-dependent; its development as a function of life fraction shows different characteristics for each material. Crack initiation occurs predominantly at second phase particles in the aluminum alloys and in slip bands or twin boundaries in the steel.

Correlation intensity data for 2024-Al and A286 stainless steel during fatigue cycling have several common characteristics. I_c is very sen-

sitive to surface deformation (slip, grain accommodation) early in the fatigue life in the low cycle regime. This sensitivity decreases at lower stress amplitudes. I_c is relatively insensitive to crack initiation but is more strongly affected by the growth of microcracks 100 microns or more in length. No unique relationship could be established between correlation intensity and microcrack length in the presence of multiple cracks. In the high to intermediate cycle regime, total fatigue life can be predicted on the basis of correlation intensity measurements made during the first fraction of 1% of the life. I_c changes observed during fatigue cycling of A286 stainless steel depend upon the slip character of the material in an analogous way to the data obtained during monotonic tensile strain. Overloads applied during fatigue cycling are detected by the I_c measurements. The I_c data can also be used to detect and evaluate cyclic creep.

These results demonstrate that the correlation intensity technique can be used in the laboratory to detect fatigue damage early in the fatigue life; as a qualitative indicator of microcrack propagation in the presence of multiple cracks; for the advance prediction of fatigue failure in the low to intermediate cycle regime under controlled conditions; and for the detection of cyclic overloads.

C. List of Publications, Presentations, and Theses/Dissertations

Publications

1. W.L. Haworth and David R. Sigler, Nondestructive Evaluation of Materials by Optical Correlation, in Review of Progress in Quantitative NDE, Vol. I (Donald O. Thompson and Dale E. Chimenti, eds.), Plenum Press, New York, 1982, pp. 675-682.

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1. David R. Sigler: "Surface Changes During Fatigue and their Evaluation by Optical Correlation," Ph.D. Dissertation, 1982.

2. Michael C. Montpetit: "Evaluation of Surface Changes During Plastic Deformation of Metals," M.S. Thesis, 1982.

3. Lu-Ling Tu: "Initiation and Growth of Cavities During Fatigue in an Al-Ca-Zn Alloy," M.S. Thesis, 1983.

4. Naresh K. Agrawal: "Evaluation of Fatigue Damage on Rough Surfaces by Optical Microscopy and Optical Correlation," M.S. Thesis, 1983.

5. Nam Soon Chang: "Metallography and Detection of Surface Deformation and Fatigue in an Age Hardening Stainless Steel," Ph.D. Dissertation, 1985 (April).

Presentations

1. Nondestructive Evaluation of Materials by Optical Correlation (W.L. Haworth and David R. Sigler), AF/DARPA Annual Review of Progress in Advanced NDE, Boulder, CO, August 1981.

2. Fatigue Detection by Optical Holography (David Sigler and W.L. Haworth), TMS-AIME Annual Meeting, Dallas, TX, February 1982 (poster session).

3. An Optical Correlation Technique for Deformation Testing (David Sigler, Michael C. Montpetit and W.L. Haworth), Symposium on Novel Techniques in Deformation Testing, TMS-AIME Fall Meeting, St. Louis, MO, October 1982.

4. Metallography of Fatigue Crack Initiation in an Overaged Aluminum Alloy (David Sigler, M.C. Montpetit and W.L. Haworth), TMS-AIME Annual Meeting, Atlanta, GA, March 1983 (poster session).

5. Fatigue Cavitation in an Al-Ca-Zn Alloy (Lu-Ling Tu, C. Gandhi and W.L. Haworth), 9th Canadian Fracture Conference, Ecole Polytechnique, Montreal, Canada, June 1983.

6. Quantitative Metallography of Fatigue in a Two-Phase Aluminum Alloy (Lu-Ling Tu, C. Gandhi and W.L. Haworth), TMS-AIME Fall Meeting, Philadelphia, PA, October 1983.

7. Evaluation of Fatigue Damage on "Rough" Surfaces (N.K. Agrawal and W.L. Haworth), TMS-AIME Fall Meeting, Philadelphia, PA, October 1983.

8. Quantitative Metallography of Fatigue Crack Initiation in Multiphase Materials (Lu-Ling Tu and W.L. Haworth), 2nd International Conference on Fatigue and Fatigue Thresholds, University of Birmingham, England, September 1984.

9. Fatigue Crack Initiation in an Age Hardening Stainless Steel (Nam Soon Chang and W.L. Haworth), TMS-AIME Fall Meeting, Detroit, MI, September 1984.

10. Fatigue Crack Initiation and Early Growth in an Age Hardening Stainless Steel (Nam Soon Chang and W.L. Haworth), ICSMA-7, Montreal, Canada, August 1985.

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